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A statistical analysis of the accuracy of MUF and field strength prediction by HFBC84, a prediction program developed for the HF Broadcast World Administrative Conference, is presented. A database of 13,054 hours of oblique sounder MOFs measured on 70 paths was used to obtain the residuals in the predicted MUFs. The MUF model had a bias of 1.17 MHz low, an rms error of 4.67 MHz, and a correlation coefficient with the measured data of 0.83. In the 4000 to 5000 km range, the MUF model has a large negative bias (predicts high). It has its highest bias during summer when it is 2.2 MHz low. During winter it has bias of 1.1 MHz low. The model reaches a minimum in bias at 1800 local time at the path midpoint; whereas, its maximum error is offset 12 hours from the minimum. A modified version of CCIR Database C was used to obtain residuals in predicted field strength; only the 81 paths for short path propagation were retained (12,277 median values). The results of the study are presented as a function of the ratio of frequency to predicted MUF. In the f/MUF range from 0.4 to 1.0 the bias in predicted field strength goes from 2.4 dB low to 3.1 dB high with a peak value at 3.8 dB low at f/MUF -0.7. In this same frequency range, the rms error goes from 12.7 dB to 13.2 dB. In the f/MUF range from 1.0 to 1.5, the bias goes from 3.1 dB high to 1.5 dB low, and the rms error goes from 13.2 dB to 13.0 dB, peaking at 17.0 dB at f/MUF -1.3. Beyond this range, both the bias and rms error increase, rapidly reaching a bias of 39.6 dB low and an rms error of 40.5 dB at f/MUF -2.0. These results indicate that the field strength method used in HFBC84 for over-the-MUF frequencies should be re-examined.

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ACCURACY OF MUF AND FIELD STRENGTH PREDICTIONS BY HFBC84

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ABSTRACT

A statistical analysis of the accuracy of MUF and field strength prediction by HFBC84, a prediction program developed for the HF Broadcast World Administrative Conference, is presented. A data base of 13,054 hours of oblique sounder MOFs measured on 70 paths was used to obtain the residuals in the predicted MUFs. The MUF model had a bias of 1.17 MHz low, an rms error of 4.67 MHz, and a correlation coefficient with the measured data of 0.83. In the 4000-5000 km range, the MUF model has a large negative bias (predicts high). It has its highest bias during summer when it is 2.2 MHz low. During winter it has a bias of 1.1 MHz low. The model reaches a minimum in bias at 1800 local time at the path mid-point; whereas, its maximum error is offset 12 hours from the minimum. A modified version of CCIR Data Base C was used to obtain the residuals in predicted field strength; only the 81 paths for short path propagation were retained (12,277 median values). The results of the study are presented as a function of the ratio of frequency to predicted MUF. In the f/MUF range from 0.4 to 1.0 the bias in predicted field strength goes from 2.4 dB low to 3.1 dB high with a peak value at 3.8 dB low at f/MUF = 0.7. In this same frequency range, the rms error goes from 12.7 dB to 13.2 dB. In the f/MUF range from 1.0 to 1.5, the bias goes from 3.1 dB high to 1.5 dB low, and the rms error goes from 13.2 dB to 13.0 dB, peaking at 17.0 dB at f/MUF = 1.3. Beyond this range, both the bias and rms error increase, rapidly reaching a bias of 39.6 dB low and an rms error of 40.5 dB at f/MUF = 2.0. These results indicate that the field strength method used in HFBC84 for over-the-MUF frequencies should be re-examined.

INTRODUCTION

The effective operation of long distance high frequency (HF) communications has increased in proportion to the ability to predict variations in the ionosphere. These variations are affected in a complex manner by solar activity, seasonal and diurnal changes, as well as latitude and longitude. Such a predictive capability has permitted communicators to optimize frequencies, antennas and other circuit parameters.

Initially, manual methods were developed for analyzing ionospheric variations on HF circuits of short, intermediate, and long distances. Because the manual methods were laborious and time consuming, various organizations have developed computer programs to analyze HF circuit performance.

One such prediction method is that adopted by the First Session of the World Administrative Radio Conference (WARC) for HF Broadcasting (1984). This computer program is commonly called HFBC84. Simultaneously, Recommendation COM 5/1 (1984) was adopted which requested the CCIR to undertake some further studies including studies concerning this method. In particular, it requested the CCIR to provide data necessary to refine two numerical constants used in the field strength method. The approach taken by the CCIR was to (1) have Interim Working Party 6/1 collate measurement data of hourly median field strengths available during 1984 and (2) establish a new Interim Working Party, 6/13, to undertake the task of determining the numerical constants. The field strength measurement data collated by IWP 6/1 is known as Data Base C. This data was used by IWP 6/13 to determine the two numerical constants in the field strength method; these constants were subsequently adopted by the CCIR in 1986.

This paper presents the uncertainty assessment of the predicted maximum usable frequency (MUF) and field strength from HFBC84. The version tested contains the new numerical constants as recommended by the CCIR. The method of HF model uncertainty assessment starts with the construction of the data bases pertinent to the parameter being assessed. For each model the observed and modeled data are compared using a data screening program (Sailors et al., 1981; Sailors et al., 1986). Error tables are produced as a function of various relevant propagation parameters.

DATA BASES USED IN THE ANALYSIS

The observed data base used in the MUF analysis consists of 13,054 median hourly MOF values derived from 70 different oblique sounder paths. Path lengths range from 196 km to 10,576 km with a relatively uniform distribution among intermediate lengths. The data is also approximately uniformly distributed in season, local time and 12 month running mean sunspot number (R_{12}) (1959-1981). It contains data from nearly all geomagnetic north latitudes with relatively less at low latitudes and very little at southern latitudes.

The field strength data base is a modified version of Data Base C. Our version of Data Base C consists of 12,277 median skywave field strength data values (dB above 1μV/m) normalized to 1 kW erp measured on 81 short paths. This differs from Data Base C in that all "long path" data has been removed.

The data making up our version of Data Base C was collected worldwide over the years 1964-1984 and contains R12 values in the range 13-165. In most cases several frequencies were used on each circuit which allows investigation of the frequency dependent aspects of the model. Unfortunately, no frequencies below 4.8 MHz are represented so the field strength variation with frequency near the LUF could not be adequately tested.

ANALYSIS PROCEDURE

The data screening computer program used to analyze the residuals between the predicted and observed data is called DASCR3. DASCR3 is able to partition a large data base, at runtime, into sub-data bases each of which contains only that data which satisfies a preset screening criteria (e.g., path length between 1000 and 2000 km). Because this partitioning is done at runtime, it is not necessary to physically retain multiple sub-data bases.

The analysis procedure consists of running the respective model programs to generate a predicted data base which matches all the conditions of the observed data. Then DASCR3 is used to determine the statistics of the residuals for the sub-data base. Statistics are determined for: (1) residual = observed datum - predicted value; (2) relative residual = residual/observed datum; and (3) absolute relative residual = absolute residual/observed datum.

MUF CALCULATION IN HFBC84

The F2 layer basic MUF calculation in HFBC84 is based on numerical maps of the F2 layer ordinary wave critical frequency, foF2, and the obliquity factor for a 3000 km path, M(3000). For paths less than 4000 km the F2(4000)MUF is determined as the product of foF2 and M(3000) at the path midpoint and the numerical factor 1.1, interpolating in R_{12} as needed. The F2 layer MUF for these paths is then found by interpolation between F2(0) MUF (i.e., foF2) and F2(4000)MUF and subsequent multiplication by an M-factor which consists of a polynominal in path length.

For paths greater than 4000 km a simple control point method utilizing the path midpoint and control points 2000 km from each terminal is used. The F2(4000)MUF is determined at each of these control points and the minimum of these values is taken as the path F2 layer MUF.

For paths less than 4000 km the basic median E-layer MUF is also calculated. In this case an empirically derived calculation of foE given by Davies (1965),

$$foE = 0.9\ [(180+1.44\ R_{12})\ \cos\chi']^{0.25}\quad \text{(MHz)},$$

is used instead of numerical maps. Here χ' is a simple function of the calculation point zenith angle (Davies, 1965). A control point method similar to the above is used in this case with points 1000 km from each terminal used for paths greater than 2000 km. The path MUF is determined as the maximum of the values determined for the F2 and E layers.

MUF ANALYSIS RESULTS

Results of our comparison for the entire data base are summarized in Table 1. Some of these results can be misleading in that they may hide a large deviation for a particular set of parameters which is compensated by a similarly large variation in the opposite sense for another set. Overall however, performance of the MUF prediction scheme in HFBC84 is quite good, with an average residual of 1.17 MHz, a rms deviation of 4.52 Mhz and an overall correlation coefficient of .827. Results for the other statistics are also shown in Table 1.

As shown in Table 1, the MUF prediction capability of HFBC84 is quite good. Results for two problem areas for which additional modeling effort may be necessary are presented below.

Figure 1 shows the average residual as a function of sounder path length. Also indicated is the standard deviation for each case. This figure indicates that HFBC84 has a marked tendency to over predict the MUF for paths in the 4000-5000 km range and under predict in the 7000-8000 km range.

Inspection of the data base shows that a significant majority of the data in the 4000 km-5000 km range is less than 4500 km and most is less than 4300 km. This is approximately the transition distance for a 2-hop mode change. Similarly, the 7000-8000 km range is just less than the distance for the next mode change. These results taken together indicate that the method used for prediction of the MUF at these critical distances is not adequate.

For paths ≥ 4000 km, the three control points are approximately coincident. Choice of the minimum as the path MUF ignores the effect of the mode switch in reducing the MUF. Determination of a hop length dependent M-factor in these cases should produce the required reduction in the MUF at these ranges.

Similarly, for paths ≤ 8000 km the M-factor has become quite large. Ignoring its effect in the MUF determination causes the under prediction seen in Figure 1. Proper inclusion of an M-factor at distances greater than 4000 km should produce improved predictions in this range.

In Figure 2 we show the average residual as a function of month (season). Again we also indicate the standard deviation for each case. This figure indicates that the model has a tendency to under predict in summer and winter months. The correlation coefficient, shown in Figure 3, also shows a reduction in summer months.

Figure 4 shows the average residual and the corresponding standard deviation as a function of midpath local time. The minimum error occurs for the hours 1500 to 1900 hours LT. The maximum bias occurs from 0500 to 1100 hours LT, an average offset of 12 hours from the minimum error. HFBC84 has its lowest standard deviation from 1800 to 0700 hours LT.

The seasonal and diurnal errors in HFBC84 probably relate to the polynominal expression used for the M factor. The expression is only a function of path length and hence must assume a constant layer height independent of season and time of day in the derivation.

Table 1. 70 path statistical analysis summary for HFBC84 MUF prediction.

STATISTIC	ANALYSIS RESULT
total path hours	13054
average residual	1.17 MHz
rms residual	4.67 MHz
average relative residual	.059
rms relative residual	.242
average absolute relative residual	.217
correlation coefficient	.827

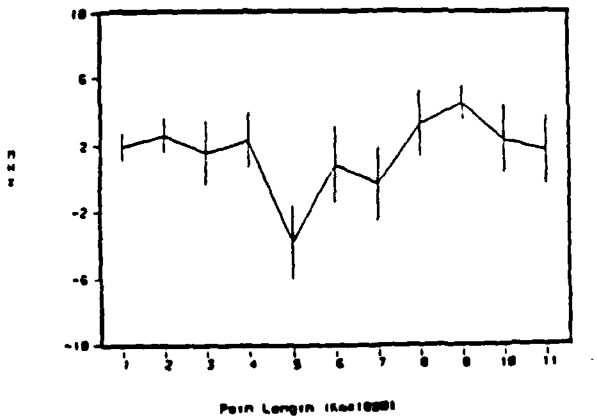

Figure 1. Average residual (bias) and standard deviation of the predicted MUF as a function of path length.

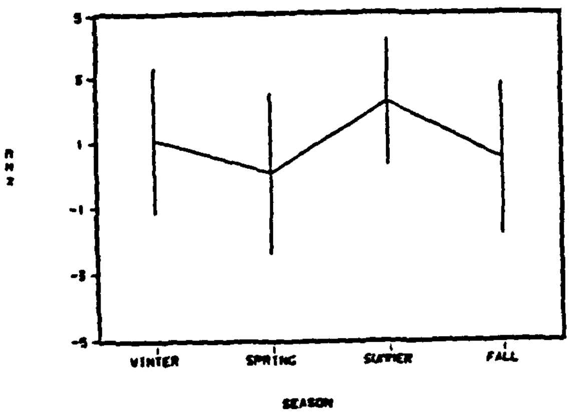

Figure 2. Average residual (bias) and standard deviation of the predicted MUF as a function of season.

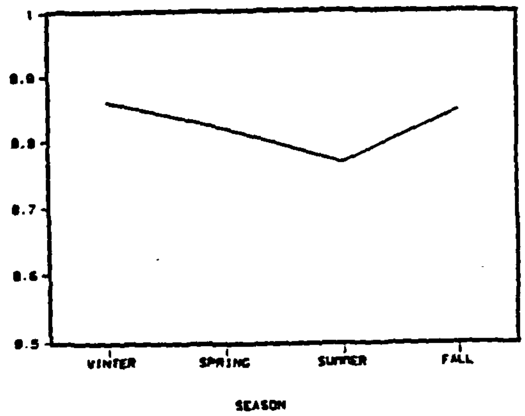

Figure 3. Correlation coefficient of the predicted MUF as a function of season.

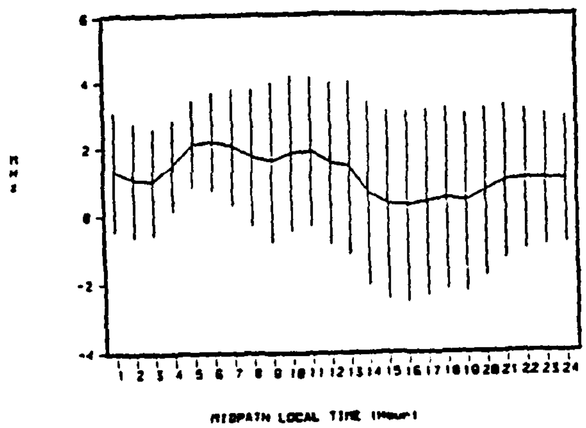

Figure 4. Average residual (bias) and standard deviation of the predicted MUF as a function of midpath local time.

FIELD STRENGTH CALCULATION IN HFBC84

The field strength calculation in HFBC84 is divided into path length regimes. One method is used for path lengths less than 7000 km; another method is used for path lengths greater than 9000 km; and from 7000 km to 9000 km the field strength is determined by interpolating as a function of range the values of the field strengths at 7000 km and 9000 km.

For paths less than or equal to 7000 km, the calculated field strength depends on whether the operational frequency is in relationship to the path MUF. For frequencies less than or equal to the MUF, the field strength calculation includes terms for basic free space loss, ionospheric absorption, ground loss, auroral absorption, transmitter power and antenna gain, and a numerical factor 7.3 dB included to account for those effects of skywave propagation not otherwise included. The ionospheric absorption is the same as used by the CCIR (1970). The nighttime ionospheric absorption is due to the work of Wakai (1961). A loss of 2 dB is assigned for each ground reflection. A table of experimentally determined factors is used to represent auroral absorption. The table depends on path length, time, season, and geomagnetic latitude. The values peak at polar latitudes with values from 3 to10 dB. For frequencies greater than the MUF, an additional loss mechanism known as over-the-MUF loss is added. This is included to account for the fact that observed field strength does not abruptly vanish as the operating frequency begins to exceed the basic MUF for a path. In HFBC85 the loss term is given by 130 [)f/MUF) and is not allowed to become larger than 85 dB.

For ranges greater than or equal to 9000 km, the HFBC84 field strength method uses the FTZ method (Beckman, 1967; Damboldt, 1975). At these path lengths, the effects of ionospheric tilts and scattering from irregularities cause contributions to the measured field strength from paths outside the main great circle path. Beckman determined that the field strength rises from a frequency (f_L) for which the field strength is some low limiting value to a peak at some intermediate frequency somewhat below the MUF, and then decreases to some low limiting value at a frequency greater than the MUF which he calls the operational MUF (fo). The f_L-fo combination then determines the transmission range of frequencies for which usable field strength may exist. The lower frequency, f_L, not a LUF, is the frequency for which the field strength is 0 dB (μV/m) for 10^3 kW effective radiated power or the frequency at which free-space field strength for 10^3 kW effective radiated power equals the ionospheric absorption assuming no other loss terms. The parameter f_L is a function of a season, the 12 month running mean sunspot number, angle of incidence at 90 km assuming mirror reflection from 300 km and hop span D for great circle path ray, solar zenith angle at a height of 90 km number of legs (twice the number of hops), winter anomaly term, and slant path length d. For F2-layer modes fo = K·MUF where K is an empirically derived factor and is a function of the MUF for the hour of interest, the maximum and minimum MUF for the 24-hour day, and a set of constants dependent on raypath azimuth. The constants used in HFBC84 have been changed from earlier values used by FTZ, and continue to change as comparison with data at FTZ warrants. Given then f_L, fó, f, the transmit power and antenna gain, the field strength can be determined from a simple expression.

FIELD STRENGTH ANALYSIS RESULTS

Results of our comparison for the entire data base are summarized in Table 2. The results are given for all observation frequencies, for observation frequencies less than equal the predicted MUF, and for observation frequencies above the MUF. Clearly, there is a considerable difference in accuracy of HFBC84 field strengths between frequencies less than equal the MUF and frequencies above the MUF. It is because of this large difference that the rest of the discussion of the field strength prediction accuracy is divided according to observation frequencies relative to the MUF.

Again as was the case in the MUF accuracy results only the problem areas can be highlighted. Figure 5 shows the average residual and its standard deviation as a function of the observation frequency f to MUF ratio. Below the MUF, the model is quite accurate; yet, it predicts somewhat high as the frequency approaches the MUF. It continues to predict high until a ratio of about 1.5 is reached. At ratios of 1.5 or larger the model predictions are clearly not satisfactory.

Figure 6 presents the average residual as a function of circuit length for both frequencies less than equal the MUF and greater than the MUF. For frequencies less than equal the MUF, HFBC84 predicts high for short paths (0-1000 km), predicts moderately high for paths from 2000 km to 7000 km, and beyond 7000 km performs poorly. For frequencies greater than the MUF, HFBC84 predicts low for path ranges from 0 to 2000 km, high for path ranges 2000 km to 7000 km, and low for path lengths greater than 7000 km.

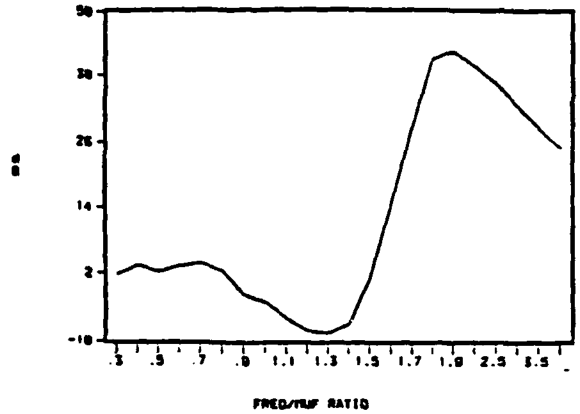

Figure 5. Average residual (bias) and standard deviation of the predicted field strength as a function of frequency to MUF ratio.

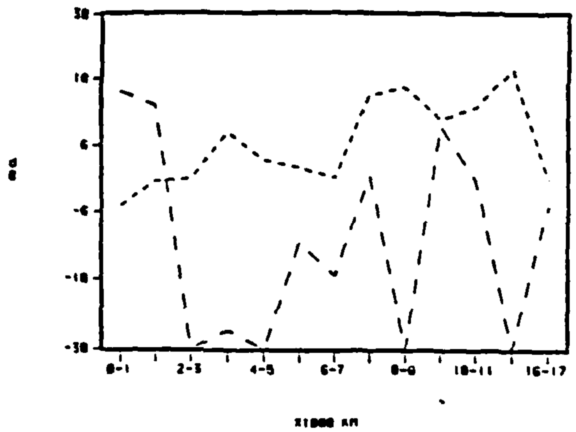

Figure 6. Average residual (bias) of the predicted field strength as a function of circuit length.

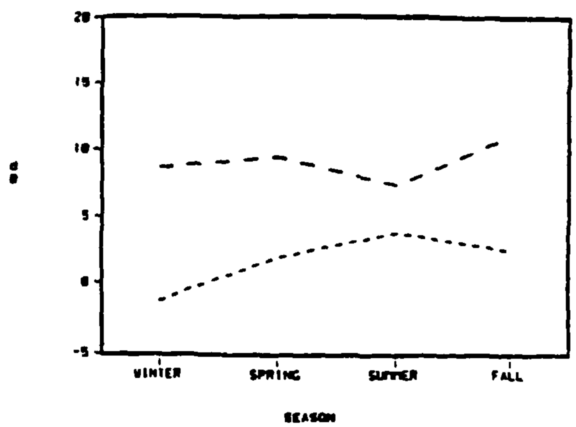

Figure 7. Average residual (bias) of the predicted field strength as a function of season.

Figure 7 shows the seasonal results for frequencies less than equal the MUF. HFBC84 shows a large bias occurring during summer. At frequencies above the MUF, HFBC84 is approximately uniform over all seasons in most cases.

Although the sunspot behavior for HFBC84 at frequencies less than equal the MUF shows an increase in bias with increasing smoothed sunspot number, the effect of varying sunspot numbers is not as large as the increase in bias for frequencies greater than the MUF as figure 8 shows.

Finally, figure 9 shows the results as a function of midpath local-time. Note that for frequencies less than equal to the MUF, the residual is uniform through the day; whereas, for frequencies greater than the MUF, the bias is a minimum at local noon with very high bias at night.

Table 2. 81 path statistical analyses summary for HFBC84 field strength prediction.

STATISTIC	OVERALL	f≤MUF	f>MUF
total path hours	12277	8783	3494
average residual	3.97 dB	1.93 dB	9.10 dB
rms residual	16.68 dB	12.06 dB	24.73 dB
average relative residual	1.32	0.04	4.53
rms relative residual	29.59	18.22	47.35
average absolute relative residual	3.21	2.34	47.35
correlation coefficient	.75	.78	.57

DISCUSSION AND RECOMMENDATIONS

The previous sections presented the results of a comparison of the accuracy of the MUF and field strength predicted from HFBC84. Functional discrepancies were noted in those sections. In this section possible causes for the discrepancies are discussed and recommendations for improvements are made. The MUF and field strength models are treated separately.

For the MUF computation, two problem areas were noted. The first dealt with the fact that the MUF calculation ignores the effect of minimum hop mode changes with increasing range. The correction is simple; insert the range of one hop of a multihop mode into the M-factor equation. This should reduce the bias occurring at ranges where mode changes occur. The seasonal and diurnal errors probably relate to the fact that the polynominal expression used for the M-factor is only a function of path length and hence must assume a constant layer height and semi-thickness independent of season and time of day. Lockwood (1983) has presented a non-iterative procedure which enables evaluation of the MUF using a distance factor, with allowance for variations in both peak height and changes in underlying plasma. If the expression for mirror height of reflection given by Lockwood (1984) for frequencies at the MUF is utilized, it would be possible to determine more precisely the effects of change in number of hops on the MUF.

In interpreting the field strength results, it should be realized that unlike ionospheric characteristics such as the MUF or foF2 which are scaled from ionograms in the same way throughout the world, procedures used to obtain field strengths vary in both method and in quality. Usually the input voltage at the receiver input in mv is measured. This measured value is then converted to field strength based on some knowledge of losses inherent in both receiving and transmitting systems. In addition, certain assumptions are made for a nominal takeoff angle for the received signal. When a data base such as Data Base C is assembled, there is some inherent inaccuracies in it which cannot be assessed.

Aside from these considerations, the overall performance of the field strength model is quite poor and could be improved, particularly in its over-the-MUF prediction method. It is recommended that the full Wheeler (1966) model be implemented in HFBC84 for ranges loss than 7000 km. This would give the needed range, diurnal, and sunspot variations not included in the present method. For short paths for frequencies less than equal the MUF, HFBC84 predicts high. This might be due in part to the method used to determine takeoff angle. HFBC84 uses an expression from Lockwood (1984) which Lockwood states is valid for frequencies 0.7 to 0.95 times the MUF and not valid for short paths. The problem with the use of the expression employed at short range is that the mirror height of reflection is no longer linear with decreasing range. At short range the mirror height of reflection is similar to that for frequencies near the MUF, only not as pronounced. Sailors et al. (1986) provides a correction to this expression for ranges less than D_{MIN} which is also given therein. Winter anomaly corrections to ionospheric absorption such as that due to Schultz and Gallet (1970) might improve its seasonal accuracy.

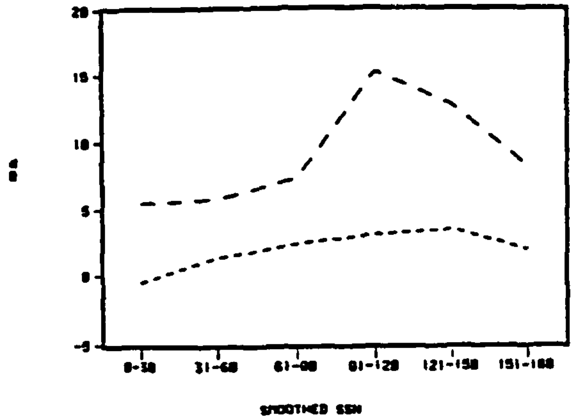

Figure 8. Average residual (bias) of the predicted field strength as a function of smoothed sunspot number.

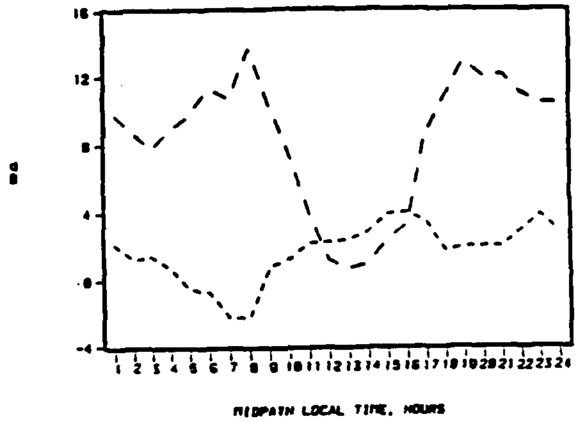

Figure 9. Average residual (bias) of the predicted field strength as a function of mid-path local time.

For ranges greater than 7000 km, where the FTZ method is employed, Sprague (1987) found that Advanced PROPHET was more accurate than HFBC84, particularly at frequencies greater than MUF. Both programs employ the FTZ method. However, Advanced PROPHET does not use the FTZ expression for operational MUF. It uses 1.85(HPF)MUF, where HPF is the 90 percentile value assuming a normal MUF distribution. For an HPF of 1.15 this is the 98.3 percentile point. At f/MUF greater than 2.0, Advanced PROPHET's bias also rapidly increases reaching a peak at f/MUF = 3.3. This might imply that 2.87(HPF)MUF be used for the operational MUF which would be equivalent to the 99.95 percentile point of a normal distribution. The trouble with the expression used in the FTZ method for operational MUF is that it is based on paths terminating in Germany. The result is that it weights the European area. In addition, FTZ changes the constants as measurements indicate. A method such as employed in Advanced PROPHET with perhaps a higher percentile point than 98.3 has more universal application.

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